Irrigation benefits for pasture production in the Wairarapa

Green S.

November 2005

Data for communication

Report to Meridian Energy Ltd

HortResearch Client Report No. 17964
HortResearch Contract No. 20365

Green S.
HortResearch Palmerston North
Batchelar Research Centre
Private Bag 11030
Palmerston North, New Zealand
Tel: +64-6-356 8080
Fax: +64-6-354 0075

DISCLAIMER

This report has been prepared by The Horticulture and Food Research Institute of New Zealand Ltd (HortResearch), which has its Head Office at 120 Mt Albert Rd, Mt Albert, AUCKLAND. This report has been approved by:

Research Scientist	Group Leader, Quality Systems
Date: 22 November 2005	Date: 22 November 2005

CONTENTS

Page

EXECUTIVE SUMMARY 1
BACKGROUND 3
MODEL APPROACH 3
SCENARIO MODELLING 6
LIMITATIONS OF THE MODELLING 9
REFERENCES 11
APPENDIX A - MASTERTON RESULTS 12
APPENDIX B - MARTINBOROUGH RESULTS 16
APPENDIX C: ANNUAL IRRIGATION DEMAND AND PASTURE PRODUCTION FOR THE WAIRARAPA 20

EXECUTIVE SUMMARY

Irrigation benefits for pasture production in the Wairarapa

Report to Meridian Energy Ltd

Green S. November 2005

Meridian Energy is interested in the benefits that irrigation may have for agricultural and horticultural activities in the Wairarapa region. HortResearch has been contracted to carry out a desktop modelling exercise to evaluate the benefits of irrigation in terms of potential pasture production. The objective is to quantify the difference in yields between dry-land and irrigated pastoral (kg DM / Ha) farms over a range of seasons, in order to understand the variability of irrigation requirements, and pasture yields.

For this task, model calculations were carried out using HortResearch's SPASMO (Soil Plant Atmosphere System Model) model. The soil water balance was calculated by considering the inputs (rainfall and irrigation) and losses (plant uptake, evaporation, runoff and drainage) of water from the soil profile. Pasture growth was modelled as being proportional to actual evaporation rate, ET_A. Model inputs included long-term (1972-2004) records of daily climate from Masterton and Martinborough. Three soil series (Ahikouka silt loam, Kokotau clay loam, and Tauherenikau shallow silt loam) were considered and calculations were made of the water balances and annual dry-matter productions from a dry-land and an irrigated farm. The key results are:

- Average pasture production from a dry-land farm near Masterton was calculated to be just 69% (Tauherenikau shallow silt loam), 73% (Kokotau clay loam) and 85% (Ahikouka silt loam) of an irrigated farm. The average annual irrigation requirement was calculated to be 350 mm yr^{-1} (Tauherenikau shallow silt loam), 400 mm yr^{-1} (Kokotau clay loam) and 250 mm yr^{-1} (Ahikouka silt loam).
- Average pasture production on a dry-land farm near Martinborough was calculated to be just 61% (Tauherenikau shallow silt loam), 65% (Kokotau clay loam) and 78% (Ahikouka

silt loam) of an irrigated farm. The average annual irrigation requirement was calculated to be 400 mm yr^{-1} (Tauherenikau shallow silt loam), 475 mm yr^{-1} (Kokotau clay loam) and 350 mm yr^{-1} (Ahikouka silt loam).

- Irrigation is expected to increase annual pasture production by between 15 and 40%, depending on soil type and rainfall. Masterton receives about 140 mm yr^{-1} more rain than Martinborough. On average, pastures in Martinborough require about 50-100 mm more irrigation each year.

The range in pasture production, as represented by $(max\text{-}min)_{dryland} / mean_{irrigated}$, is somewhere between 28 and 43% on a dryland farm. The corresponding range on an irrigated farm is just 20%. These results confirm that irrigation reduces the year-to-year variability in pasture production.

Realizing these potential yield gains in an efficient manner will require careful management of irrigation, especially on some of the very stony free-draining soils.

For further information contact: Steve Green
HortResearch Palmerston North
Batchelar Research Centre
Private Bag 11030
Palmerston North, New Zealand
Tel: +64-6-356 8080
Fax: +64-6-354 0075
Email: sgreen@hortresearch.co.nz

BACKGROUND

Meridian Energy is interested in the benefits irrigation may have for agricultural and horticultural activities in the Wairarapa region. It is anticipated that irrigation will offer both an increase in yield and an increase in the reliability of the yield from year to year. Both the total amount of pasture produced and the variability of that production on an annual basis are important in determining the type and intensity of farming system that can be adopted.

HortResearch has been contracted to carry out a desktop modelling exercise to evaluate the benefits of irrigation in terms of potential pasture production. The results were requested in tabular form, with commentary limited to details of the data sources, descriptions of the scenarios modelled, the assumptions used and any limitations applicable.

The objective of the modelling was to:

- Quantify the difference in yields between dry-land and irrigated pastoral (kg DM / Ha) farms for two representative soils (low and medium soil moisture holding capacity) for the Wairarapa region
- Compare the dry-land and irrigated pastoral systems over a representative range of seasons (30-year simulation, based on actual climatic data from the Wairarapa region), in order to understand the variability of irrigation requirements, and pasture yields.

The results will be used as the driver for decisions on the land use diversification and intensification options possible. The results also create output parameters to be used in subsequent farm financial performance modelling. Model output includes dry matter production on an annual basis for both dry-land and irrigated systems, the depth of water applied during the irrigation season, and a ranking of the drought return period.

MODEL APPROACH

Model calculations were carried out using HortResearch's SPASMO model (Green et al. 1999; Rosen et al. 2004). The soil water balance was calculated by considering the inputs (rainfall and irrigation) and losses (plant uptake, evaporation, runoff and drainage) of water from the soil profile. Pasture water use was modelled using the FAO crop-factor approach that relates water use to the prevailing weather and time of year (Allen et al. 1998). Measured values of global radiation, air temperature, relative humidity and wind speed were used to calculate the reference evaporation rate, ET_O [mm d^{-1}] as:

$$ET_0 = \frac{\frac{s}{\lambda}(R_N - G_H) + \gamma \frac{900}{(T+273)} u_2 (e_s - e_a)}{s + \gamma\,(1 + 0.34 u_2)} \qquad \text{[Eq. 1]}$$

where R_N [MJ m^{-2} d^{-1}] is the net radiation, G_H [MJ m^{-2} d^{-1}] is the ground heat flux, T [^{o}C] is the mean air temperature, e_s [kPa] is the saturation vapour pressure at the mean air temperature, e_a (kPa) is the mean actual vapour pressure of the air, u_2 [m s-1] is the mean wind speed at 2 m height, s [Pa ^{o}C^{-1}] is the slope of the saturation vapour-pressure versus temperature curve, γ [66.1 Pa] is the psychrometeric constant, and λ [2.45 MJ kg^{-1}] is the latent heat of vaporisation for water. Input data were compiled from the national climate database using long-term (1972-2004) records from Masterton [Te Ore Ore (7578) and East

Taratahi (2610)] and Martinborough [Martinborough (SN2651 & SN 21938) and Tauherenikau (SN2623)].

Pasture production was modelled in the following manner. To an acceptable first approximation, dry matter production is proportional to transpiration (McAneney and Judd 1983). Furthermore, for full-cover pasture (leaf area index > 3), nearly all the evapotranspiration is transpiration (Kerr et al. 1986). Thus, we modelled pasture growth as being proportional to actual evaporation rate, ET_A,

$$G = k\, ET_A. \qquad \text{[Eq. 2]}$$

The proportionality constant, k with units of kg DM ha^{-1} mm^{-1}, is a site-specific factor which could also be an index of soil fertility status. A set value of k = 19 kg DM ha^{-1} mm^{-1} has been reported by Moir et al. (2000) for a range of pastures in the Wairarapa. This value of k is consistent with our own studies of pasture production on an irrigated dairy farm in Hawke's Bay (Green et al. 2003), and a dry-land farm in the central North Island (Webby et al. 2003).

Transpiration proceeds at a maximum (climate dependent) rate, providing soil water and nutrients are non-limiting. However, once the root-zone water deficit increases above a given threshold, pastures exhibit symptoms of water stress that reduce transpiration and curtail productivity.

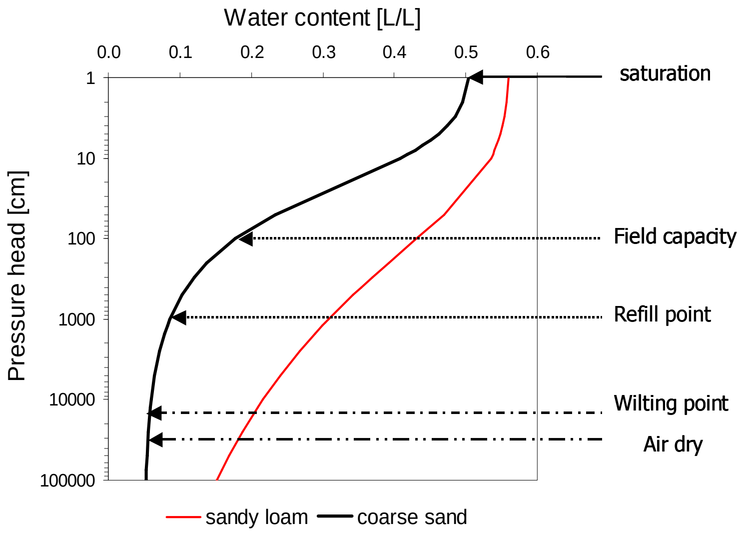

Figure 1. The soil's water retention properties are defined by the relationship between the matric potential (pressure head) and the volumetric water content.

SPASMO models the soil's water content using a water capacity approach of Hutson and Wagenet (1993). The calculations are based on soil hydraulic properties derived from the New Zealand Soils database (Hewitt 1998; Willoughby et al. 2003). Following a heavy rainfall or a large irrigation, the soil first drains for a few days until field capacity, θ_{FC} [L/L], is reached (Figure 1). Thereafter, as the soil dries, it gets progressively more difficult for plant roots to extract moisture. Eventually, the soil water content reaches the point where no more water uptake can occur and the pasture wilts. Classically, this water content, θ_{WP}, is defined as the 'permanent wilting point'. The total plant-available water is defined as $T_{AW} = (\theta_{FC}-\theta_{WP})/Z_R$, which depends on the depth of the pasture roots, Z_R [mm], and the water holding capacity, $(\theta_{FC}-\theta_{WP})$, of the soil. The root depth is set equal to 0.5 m (Allen et al. 1998).

Although soil water is theoretically available to the plants all the way down to wilting point, pasture production will often be curtailed well before this moisture level is reached. The 're-fill point' for irrigation is defined using a fraction, p, of the total available water i.e. $\theta_{SP} = \theta_{FC}$

– $p(\theta_{WP}-\theta_{FC})$. A typical value of p equals 0.60 for pastures in the Waikato (McAneney et al., 1982) and Taranaki (Parfitt et al. 1985) regions. We have been more conservative and, for the purpose of allocation, have assumed p=0.50. The effect of a mild-water stress is modelled by reducing ET_O whenever soil moisture decreases below θ_{SP}. This is achieved by multiplying ET_O by a water stress coefficient, K_S, which decreases linearly from 1.0 to 0.0 for soil moistures in the range $\theta_{SP} > \theta > \theta_{WP}$.

The surface runoff component of SPASMO is based on a daily rainfall total and uses the Soil Conservation Service (SCS) curve number approach (Williams 1991). Surface runoff is calculated as:

$$Q = \frac{(R-0.2S)^2}{R+0.8S}, \qquad R > 0.2S$$
$$Q = 0, \qquad\qquad , \qquad R \le 0.2S \qquad \text{[Eq. 3]}$$

where Q [mm] is the daily runoff , R [mm] is the daily rainfall, and S [mm] is the retention parameter that reflects variations among soils, land use and management. The retention parameter, S, is related to the curve number, CN, using the SCS equation (Soil Conservation Service, 1972)

$$S = 254\left(\frac{100}{CN} - 1\right) \qquad \text{[Eq. 4]}$$

where the constant, 254, gives S in millimetres. The average curve number can be obtained easily for any area of land use type from the SCS Hydrology Handbook (Soil Conservation Service). Pasture in good condition on a free draining soil has a low CN value (39), while pasture in poor condition on a poorly drained soil has a high CN value (89). The SCS runoff calculation has an additional adjustment to S, to express the effect of slope and soil moisture (Williams 1991). In the calculations presented here, we have assumed the field slope was always less than 5% and have used a reference CN value for pasture in average condition. The only other adjustment with respect to run-off was to include any changes in S that were due to different soil moisture levels.

SPASMO runs on a daily time step. The water balance calculations are made in the following sequence:

- Subtract evaporation from the soil surface
- Calculate transpiration losses and partition water uptake in proportion to the depth-wise pattern of roots
- If there is rain or irrigation, then perform the leaching process
- Redistribute water through the soil profile according to soil matric potential
- Repeat the process for the next day.

For modelling purposes, the irrigation regime applied 25 mm of water only on those days when the pasture was in need of it. This ‘need’ was determined when a given fraction of readily available moisture (p) has been extracted from the root-zone soil. Irrigation was not applied if there was already sufficient water in the root-zone soil, or if the daily rainfall exceeded 5 mm. We consider this irrigation regime as being “optimum” for the purpose of calculating the monthly and annual irrigation needs.

SCENARIO MODELLING

Two scenarios (dry-land and irrigated pasture) were simulated for three soil series (Ahikouka silt loam, Kokotau clay loam & Tauherenikau shallow silt loam) and two climates (Masterton and Martinborough). The results are presented in tabular form in Appendices A and B. A brief description of these is presented below.

Scenario 1 – Masterton

Masterton has an average annual rainfall of 933 mm yr^{-1} (Table A1). One year in ten the annual rainfall exceeds 1174 mm yr^{-1}. The annual ET is calculated to be 781 mm yr^{-1} (Table A2) and the average annual dry-matter production for an irrigated pasture in good condition is calculated to be 14840 kg ha^{-1} yr^{-1} (Table A3). Pasture production on a dry-land farm declines to about 69% (Tauherenikau shallow silt loam), 73% (Kokotau clay loam) and 85% (Ahikouka silt loam) of the irrigated farm, on average (Tables A7-9 & Figure 2). The average annual irrigation requirement for pasture in Masterton is calculated to be 350 mm yr^{-1} (Tauherenikau shallow silt loam), 400 mm yr^{-1} (Kokotau clay loam) and 250 mm yr^{-1} (Ahikouka silt loam) (Tables A10-12 & Figure 3).

Scenario 2 – Martinborough

Martinborough has an average annual rainfall of 794 mm yr^{-1} (Table B1). One year in ten the annual rainfall exceeds 996 mm yr^{-1}. The annual ET is calculated to be 796 mm yr^{-1} (Table B2) and the annual dry-matter production for an irrigated pasture in good condition is calculated to be 15115 kg ha^{-1} yr^{-1} (Table B3), on average. Pasture production on a dry-land farm declines to about 61% (Tauherenikau shallow silt loam), 65% (Kokotau clay loam) and 78% (Ahikouka silt loam) of the irrigated farm, on average (Tables B7-9 & Figure 3). The average annual irrigation requirements for pasture in Masterton are calculated to be 400 mm yr^{-1} (Tauherenikau shallow silt loam), 475 mm yr^{-1} (Kokotau clay loam) and 350 mm yr^{-1} (Ahikouka silt loam) (Tables B10-12 & Figure 4).

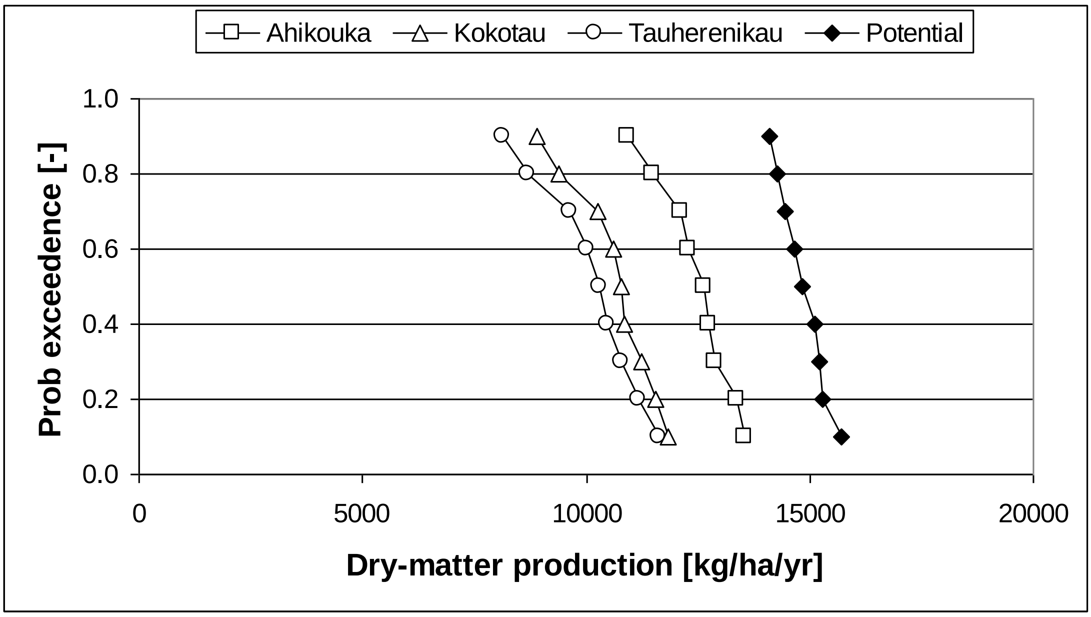

Figure 2. Probability of exceedence for annual dry-matter production [kg/ha] from a dry-land farm at Masterton (Te Ore Ore) on an Ahikouka silt loam, Kokotau clay loam, and Tauherenikau shallow silt loam soil. The solid symbol represents potential production from an irrigated farm, calculated via Eqns 1 & 2.

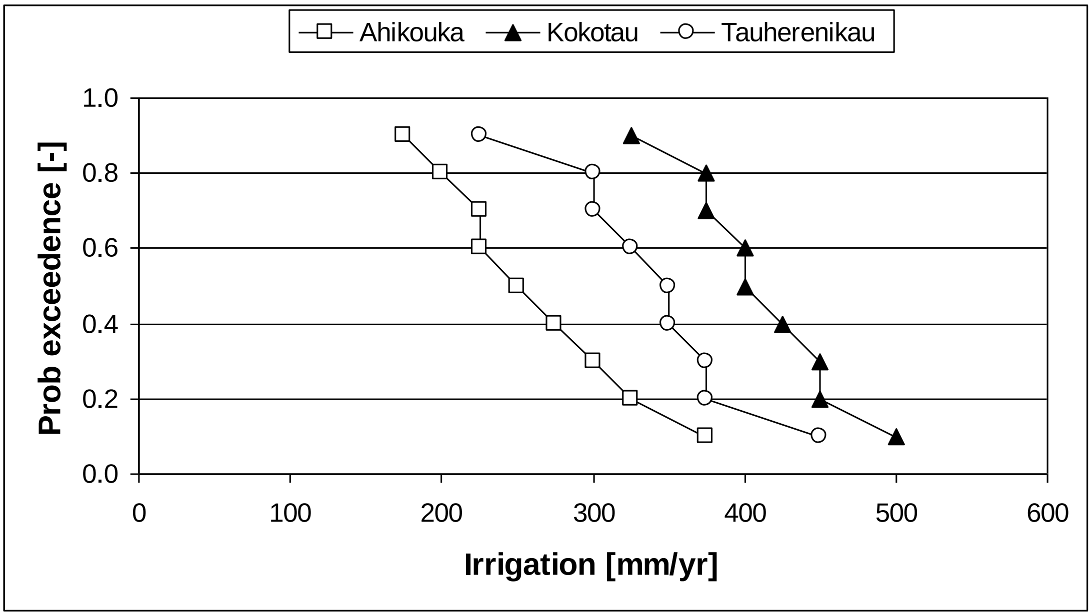

Figure 3. Probability of exceedence for the annual irrigation requirements [mm yr^{-1}] for an irrigated farm at Masterton (Te Ore Ore) on an Ahikouka silt loam, Kokotau clay loam, and Tauherenikau shallow silt loam soil. The SPASMO calculations assume that 100% of the irrigation water is available to the pasture (see text for details).

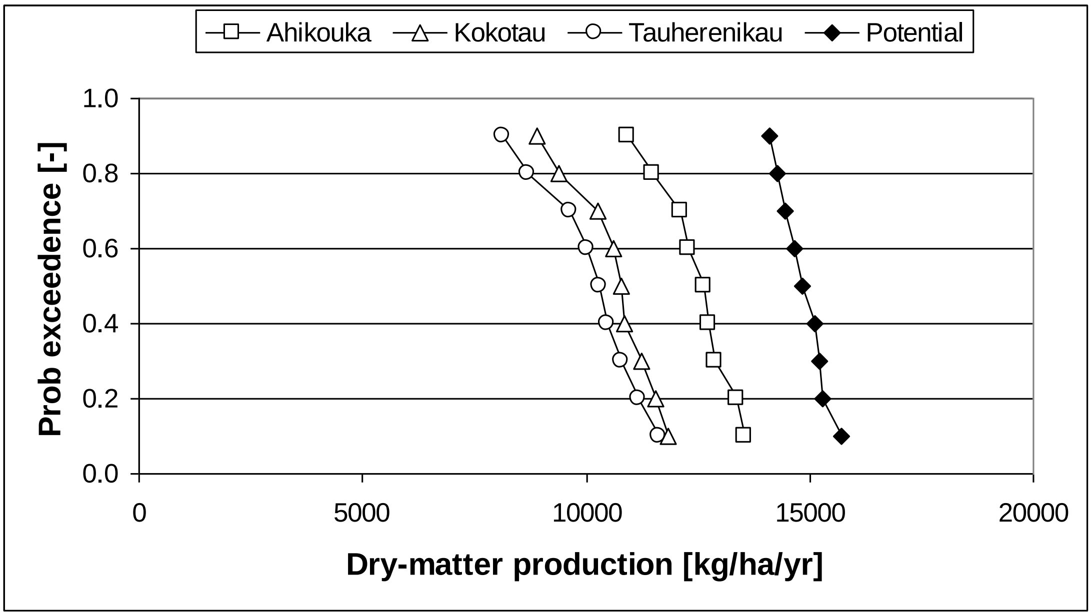

Figure 4. Probability of exceedence for annual dry-matter production [kg/ha] from a dry-land farm at Martinborough on an Ahikouka silt loam, Kokotau clay loam, and Tauherenikau shallow silt loam soil. The solid symbol represents potential production from an irrigated farm, calculated via Eqns 1 & 2.

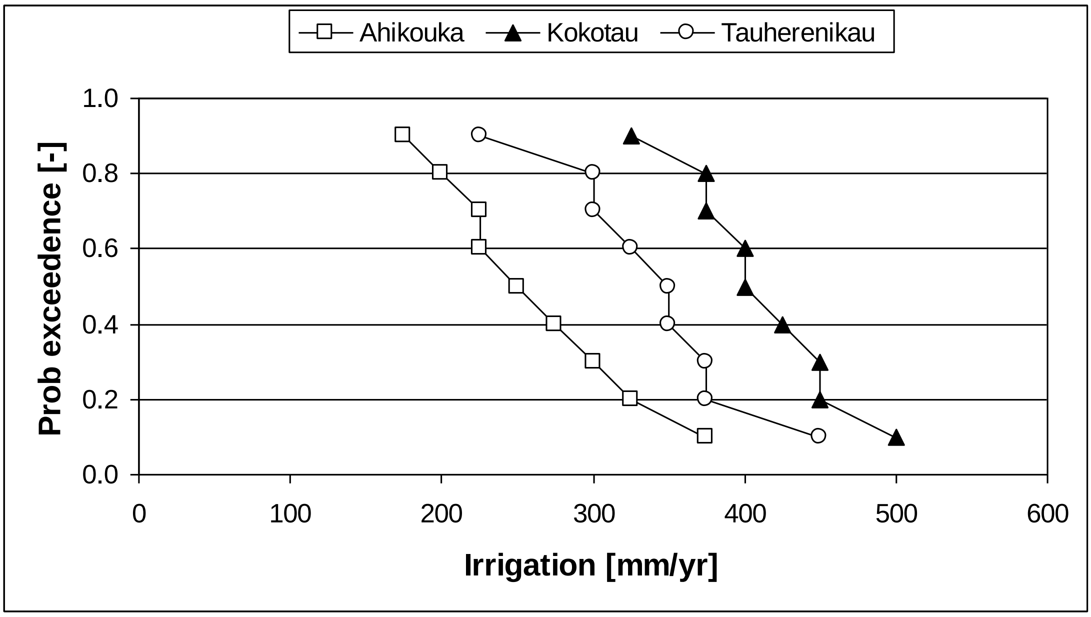

Figure 5. Probability of exceedence for the annual irrigation requirements [mm yr^{-1}] for an irrigated farm at Masterton (Te Ore Ore) on an Ahikouka silt loam, Kokotau clay loam, and Tauherenikau shallow silt loam soil. The SPASMO calculations assume that 100% of the irrigation water is available to the pasture (see text for details).

Model predictions of annual pasture production are summarized in Tables 1 & 2. Irrigation is expected to increase annual pasture production by between 15 and 40% depending on soil type and rainfall. Masterton receives about 140 mm yr^{-1} more rain than Martinborough. On average, pastures in Martinborough require about 50-100 mm more irrigation, each year.

Soils with lower water holding capacities, or higher stone fractions, are expected to exhibit the greatest potential benefit from irrigation. The coefficient of variability (CV = standard deviation divided by mean) in pasture production from a dry-land farm ranges between 8 and 13% at Masterton, and between 10 and 17% at Martinborough. The corresponding CV on an irrigated farm is less than 5%. The range in pasture production, as represented by $(\text{max-min})_{\text{dryland}} / \text{mean}_{\text{irrigated}}$, is somewhere between 28 and 43% on a dryland farm. The corresponding range on an irrigated farm is just 20%. This result confirms that irrigation helps reduce the year-to-year variability in pasture production.

Appendix C provides a risk assessment of the annual irrigation demand and pasture production for selected soils in the Wairarapa.

Realizing these potential yield gains in an efficient manner will require careful management of irrigation, especially on some of the very stony free-draining soils.

Table 1. The effect of soil type on annual pasture production (July-July) from a dry-land farm at Masterton and Martinborough. The simulations are based on daily climate data from 1972-2004. CV = (standard deviation divided by mean) represents the coefficient of variation.

Location	Soil	minimum	maximum	mean	standard deviation	CV [%]
Masterton Te Ore Ore	AHIKOUKA SILT LOAM	10123	14108	12486	998	8.0
	KOKOTAU CLAY LOAM	7868	12838	10698	1137	10.6
	TAUHERENIKAU SHALLOW SILT LOAM	7002	12779	10242	1358	13.3
Martinborough	AHIKOUKA SILT LOAM	9339	14345	11674	1188	10.2
	KOKOTAU CLAY LOAM	6977	12703	9718	1353	13.9
	TAUHERENIKAU SHALLOW SILT LOAM	6004	12580	9101	1523	16.7

Table 2. The effect of soil type on annual pasture production (July-July) from a dry-land farm at Masterton and Martinborough. The simulations are based on daily climate data from 1972-2004. CV = (standard deviation divided by mean) represents the coefficient of variation.

Location	Soil	minimum	maximum	mean	std	CV
Masterton Te Ore Ore	AHIKOUKA SILT LOAM	12943	16194	14875	696	4.7
	KOKOTAU CLAY LOAM	12943	16194	14875	696	4.7
	TAUHERENIKAU SHALLOW SILT LOAM	12943	16194	14875	696	4.7
Martinborough	AHIKOUKA SILT LOAM	13102	16410	15073	669	4.4
	KOKOTAU CLAY LOAM	13102	16410	15073	669	4.4
	TAUHERENIKAU SHALLOW SILT LOAM	13102	16410	15073	669	4.4

LIMITATIONS OF THE MODELLING

Running the model with the evaporation equal to ET_O provides a useful benchmark as it simulates production with irrigation. The difference between this and production simulated without irrigation indicates how much water stress will affect pasture yield. The simple *k*-factor used to relate pasture production to actual ET losses has been assigned a value of k=19 kg dry-matter per mm of evaporation. This *k*-value is based on experimental data from pastures in the Wairarapa and Central Hawke's Bay, and is therefore expected to provide a reasonable fit to reality. However, there are many other factors affecting pasture production that have not been considered.

Moir (2000) points out that a possible weakness of the model is the way in which temperature is treated. In winter, pasture growth is likely to be more temperature sensitive than the reference crop evaporation, while in summer the reverse is likely to be true. Nutrients (N & P) may also be limiting e.g. on soils that have a low-P status, the maximum productivity may be a low as 8-10 T/ha rather than 16 T/ha (Moir 2000). Furthermore, the behaviour of pasture and soil following a prolonged dry spell is complicated by scenesence and phase lags in recovery that are not included in the simple modelling approach. On a ‘rewetted’ dry soil, lag phases in pasture growth response because of increased moisture may, in part, be attributed to soil microbial processes and the associated change in nutrient availability to plants (Moir 2000). Current understanding of these microbial processes is limited.

Table 3. Application efficiency for a range of irrigation systems (from McIndoe 2002).

Irrigation system	Application efficiency
Centre pivot - fixed	90-95
Centre pivot - towable	85-90
Rotary boom	80-85
K line	80-90
Low pressure boom	70-75
Big gun	65-75

Finally, the irrigation application efficiency is not addressed by the software. SPASMO assumes that 100% of the irrigation water is available to the pasture. In practical terms, not all of the applied water will enter the soil. McIndoe (2002) estimated typical losses from New Zealand pressurized irrigation systems as 0-1% losses from leaking pipes, < 3% losses from evaporation in the air, < 5% losses from wind blowing water off the target area, < 2% losses from surface runoff, and < 5% interception losses from the canopy. The major loss (5-30%) is attributed to uneven/excessive application depths and rates.

Inefficiency means that more water than average needs to be applied to replenish the root-zone water deficit. For example, a system with uniformity[1] of 70% (typical of many irrigation systems in New Zealand) needs to apply about 45 mm of irrigation in order to replace a 25 mm soil water deficit over 90% of the field (McIndoe 2002). Improving the uniformity to 90% still means that 30 mm of irrigation is required to replace a 25 mm water deficit. Application efficiency can be expressed via the ratio of the depth of water that enters the root-zone soil to the total volume of water applied (Table 3). Centre pivots are the most efficient system for pasture irrigation, yet they still have losses of between 5 to 10%. Inefficiency in irrigation will likewise affect pasture production although we have no means to estimate such an effect.

- **SPASMO assumes that 100% of the applied water enters the root zone soil. Adding an extra 20% to the SPASMO recommendation should provide an operational margin that accounts for application efficiency for all but the least efficient systems (e.g. low pressure boom and big gun irrigators).**

[1] Uniformity coefficient = $100\left[1-\frac{\Sigma\left|X-\overline{x}\right|}{\Sigma X}\right]$ where X = actual depth and $\overline{x}$ = average depth [mm]

REFERENCES

Allen, R.G., Pereria, L.S., Raes, D., and Smith, M., 1999. Crop Evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56, FAO, Rome, 301 pp.

Doorenbos, J., and Pruitt W.O., 1977. Crop water requirements. FAO Irrigation and Drainage Paper No 24, Rome, Italy. Food and Agricultural Organisation of the United Nations, pp. 144.

Green, S.R., Clothier, B.E., Mills, T.M., and Millar, A., 1999. A risk assessment of the irrigation requirements of field crops in a maritime climate. Journal of crop production, 2: 353-377.

Green S, van den Dijssel C, and Clothier B, 2004. Monitoring of nitrates within the Hawke's Bay: a case study of Ingleton farms near Tikokino. Report to Hawke's Bay Regional Council. HortResearch Client Report No: S/320132/01

Hewitt, A.E. 1998. New Zealand soil classification. Manaaki Whenua Press:, Lincoln, New Zealand.

Hutson and Wagenet, 1993. A pragmatic field-scale approach for modelling pesticides. Journal of Environmental Quality, 22: 494-499.

Kerr, J.P., de Ruiter, J.M., and Hall, A.J., 1986. The magnitude and variability of seasonal water deficits for pasture and crop growth. New Zealand Agricultural Science 20: 13-18.

McAneney, K.J., Judd, M.J., and Weeda, W.C., 1982. Loss in monthly pasture production resulting from dryland conditions in the Waikato. NZ Journal of Agricultural Research, 25: 151-156.

McIndoe, I., 2002. Irrigation efficiency enhancement – Stage 1. Report prepared for LandWISE Hawkes's Bay. Report No 4452/16a, Lincoln Environment, 46 pp.

Moir, J.L, Scotter, D.R., Hedley, M.J. and Mackay, A.D., 2000. A climate-driven, soil fertility dependent, pasture production model. NZ Journal of Agricultural Research, 43: 491-500.

Parfitt, R.L., Roberts, A.H.C., Thomson, N.A., and Cook, F.J., 1985. Water use, irrigation and pasture production on a Stratford silt loam. NZ Journal of Agricultural Research, 28: 393-401.

Rosen, M.R., Reeves, R.R., Green S.R., Clothier, B.E., and Ironside, N, 2004. Prediction of groundwater nitrate contamination after closure of an unlined sheep feed lot in New Zealand. Vadose Journal, 3:990-1006.

Press, W.H., Flannery, B.P., Teukolsky, S.A., and Vetterling, W.T., 1989. Numerical Recipes – the art of scientific computing. Cambridge, UK. Cambridge University Press, pp. 702.

Soil Conservation Service, 1972. Estimation of direct runoff from storm rainfall. USDA. (downloadable copy from www.info.usda.gov/CED/ftp/CED/neh630-ch10.pdf)

Webby R, Hall J, and Green S 2003. Evaluation of financial returns from Irrigation. Report to Te Pouakani Farms, AgResearch Client Report, 14 pp.

Williams, J.R., 1991. Runoff and water erosion. In J. Hanks and J.T. Ritchie (Eds.), Modelling plant and soil systems. Agonomy No. 31 series, American Soc. Agronomy, Madison, USA.

Willoughby, E.J.; Wilde, R.H.; McLeod, M.; Hewitt, A.E. and Webb, T.H. 2001: National Soils Database Audit: A document describing Landcare Research soils data. Landcare Research. Unpublished Report.

APPENDIX A - MASTERTON RESULTS

Table A1. Probability of exceedence for rainfall [mm] at Masterton (Te Ore Ore). The data are for the years 1972-2004.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	20	26	30	40	54	70	73	79	88
Feb	18	31	32	36	42	57	65	91	102
Mar	36	43	50	55	64	68	70	81	107
Apr	29	32	40	52	62	68	75	84	135
May	37	53	63	75	84	90	95	112	132
Jun	43	55	69	77	87	100	108	121	138
Jul	53	61	84	92	106	110	119	131	161
Aug	40	45	59	70	77	92	104	125	139
Sep	35	43	47	57	67	69	75	88	130
Oct	34	45	50	60	65	76	81	99	128
Nov	28	52	64	71	75	80	83	92	110
Dec	26	36	41	54	59	69	83	90	107
Annual	723	788	815	887	933	950	970	1056	1174

Table A2. Probability of exceedence for ET [mm] from an irrigated pasture at Masterton (Te Ore Ore) on an Ahikouka silt loam.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	128	129	133	135	137	139	143	145	149
Feb	93	97	101	102	106	108	111	115	119
Mar	67	71	74	75	76	77	79	80	83
Apr	33	34	35	36	36	36	37	38	39
May	9	9	9	9	9	10	10	10	11
Jun	2	2	2	2	3	3	3	3	3
Jul	3	4	4	4	5	5	5	5	6
Aug	20	20	21	21	21	21	22	22	22
Sep	45	46	48	49	50	51	52	53	55
Oct	81	82	85	87	89	91	92	94	95
Nov	102	106	109	110	111	113	115	116	119
Dec	121	123	127	131	134	137	140	144	151
Annual	743	752	760	771	781	796	801	805	826

Table A3. Probability of exceedence for dry-matter production [kg/ha] from an irrigated pasture at Masterton (Te Ore Ore) on an Ahikouka silt loam.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	2430	2455	2519	2557	2605	2647	2711	2761	2822
Feb	1774	1851	1911	1932	2006	2044	2103	2181	2259
Mar	1271	1343	1402	1423	1448	1471	1497	1522	1584
Apr	620	640	665	676	683	689	702	717	734
May	163	166	169	173	179	181	185	195	215
Jun	30	34	38	39	48	51	53	58	61
Jul	66	71	80	83	89	90	96	103	112
Aug	377	388	394	396	402	404	412	417	426
Sep	850	882	911	928	949	960	995	1004	1053
Oct	1546	1567	1616	1652	1693	1720	1749	1779	1805
Nov	1938	2010	2069	2088	2107	2145	2181	2206	2252
Dec	2291	2333	2421	2493	2544	2605	2666	2727	2860
Annual	14117	14280	14442	14649	14841	15124	15213	15293	15690

Table A4. Probability of exceedence for ET [mm] losses from a dry-land pasture at Masterton (Te Ore Ore) on an Ahikouka silt loam.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	57	65	80	83	89	98	111	116	123
Feb	45	52	57	68	71	76	82	86	93
Mar	41	56	63	65	66	69	73	74	77
Apr	33	34	35	35	36	36	36	37	38
May	9	9	9	9	9	10	10	10	11
Jun	2	2	2	2	3	3	3	3	3
Jul	3	4	4	4	5	5	5	5	6
Aug	20	20	21	21	21	21	22	22	22
Sep	45	46	48	49	50	51	52	53	55
Oct	81	82	85	87	89	91	92	94	95
Nov	100	104	106	108	110	111	113	114	116
Dec	82	88	97	105	110	113	119	121	126
Annual	574	604	638	646	665	670	678	703	714

Table A5. Probability of exceedence for ET [mm] losses from a dry-land pasture at Masterton (Te Ore Ore) on a Kokotau clay loam.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	39	45	50	58	72	78	86	92	100
Feb	33	41	44	49	56	64	69	74	78
Mar	36	41	49	56	59	64	65	71	76
Apr	29	32	33	34	35	35	36	36	38
May	9	9	9	9	9	10	10	10	11
Jun	2	2	2	2	3	3	3	3	3
Jul	3	4	4	4	5	5	5	5	6
Aug	20	20	21	21	21	21	22	22	22
Sep	45	46	48	49	50	51	52	53	55
Oct	76	80	82	82	85	85	86	89	90
Nov	58	81	83	84	89	93	95	99	104
Dec	51	57	68	73	76	86	95	101	114
Annual	469	494	539	559	567	571	592	608	622

Table A6. Probability of exceedence for ET [mm] losses from a dry-land pasture at Masterton (Te Ore Ore) on a Tauherenikau shallow silt loam.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	28	31	36	48	59	67	81	84	96
Feb	23	31	35	38	48	57	63	73	76
Mar	27	36	46	49	56	59	64	71	76
Apr	26	30	33	34	35	35	36	36	37
May	9	9	9	9	9	10	10	10	11
Jun	2	2	2	2	3	3	3	3	3
Jul	3	4	4	4	5	5	5	5	6
Aug	20	20	21	21	21	21	22	22	22
Sep	45	46	48	49	50	51	52	53	55
Oct	80	82	85	85	87	89	89	91	93
Nov	59	79	82	89	92	95	101	103	109
Dec	37	45	56	62	66	72	88	96	109
Annual	428	458	508	527	541	551	568	588	612

Table A7. Probability of exceedence for dry-matter production [kg/ha] from a dry-land pasture at Masterton (Te Ore Ore) on a Ahikouka silt loam.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	1088	1238	1528	1570	1690	1854	2115	2200	2335
Feb	857	989	1092	1292	1348	1448	1558	1641	1761
Mar	786	1062	1198	1230	1256	1303	1385	1413	1455
Apr	618	637	661	666	676	684	690	709	727
May	163	166	169	173	179	181	185	195	215
Jun	30	34	38	39	48	51	53	58	61
Jul	66	71	80	83	89	90	96	103	112
Aug	377	388	394	396	402	404	412	417	426
Sep	850	882	911	928	949	960	995	1004	1053
Oct	1546	1567	1616	1652	1693	1720	1749	1779	1805
Nov	1893	1974	2014	2054	2092	2101	2138	2157	2206
Dec	1549	1678	1839	1999	2092	2151	2255	2291	2388
Annual	10914	11476	12122	12272	12629	12734	12876	13353	13557

Table A8. Probability of exceedence for dry-matter production [kg/ha] from a dry-land pasture at Masterton (Te Ore Ore) on a Kokotau clay loam.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	741	852	951	1100	1361	1482	1633	1751	1900
Feb	618	770	832	939	1060	1212	1309	1414	1482
Mar	676	786	939	1073	1116	1210	1240	1345	1442
Apr	560	613	623	640	661	674	684	690	717
May	163	166	169	173	179	181	185	195	215
Jun	30	34	38	39	48	51	53	58	61
Jul	66	71	80	83	89	90	96	103	112
Aug	377	388	394	396	402	404	412	417	426
Sep	850	882	911	928	949	960	995	1004	1053
Oct	1451	1519	1549	1565	1608	1620	1643	1693	1711
Nov	1111	1535	1578	1603	1693	1767	1807	1886	1967
Dec	969	1087	1286	1386	1453	1643	1804	1913	2166
Annual	8915	9384	10249	10625	10773	10855	11246	11544	11826

Table A9. Probability of exceedence for dry-matter production [kg/ha] from a dry-land pasture at Masterton (Te Ore Ore) on a Tauherenikau shallow silt loam.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	525	592	690	913	1130	1276	1542	1602	1825
Feb	433	581	668	727	917	1079	1193	1392	1441
Mar	516	683	876	924	1066	1129	1209	1343	1442
Apr	498	561	618	637	658	673	684	689	710
May	163	166	169	173	179	181	185	195	215
Jun	30	34	38	39	48	51	53	58	61
Jul	66	71	80	83	89	90	96	103	112
Aug	377	388	394	396	402	404	412	417	426
Sep	850	882	911	928	949	960	995	1004	1053
Oct	1519	1561	1608	1618	1652	1693	1698	1738	1768
Nov	1120	1499	1562	1700	1752	1805	1910	1948	2077
Dec	708	849	1057	1181	1263	1376	1675	1830	2071
Annual	8126	8694	9650	10007	10287	10475	10783	11166	11636

Table A10. Probability of exceedence for irrigation [mm] requirements of pasture at Masterton (Te Ore Ore) on a Ahikouka silt loam.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	25	50	50	50	75	75	100	100	100
Feb	25	25	50	50	50	50	75	75	100
Mar	0	0	0	0	25	25	25	25	50
Apr	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0
Jun	0	0	0	0	0	0	0	0	0
Jul	0	0	0	0	0	0	0	0	0
Aug	0	0	0	0	0	0	0	0	0
Sep	0	0	0	0	0	0	0	0	0
Oct	0	0	0	0	25	25	25	25	25
Nov	0	25	25	25	25	25	50	50	50
Dec	25	25	25	50	75	75	75	100	100
Annual	175	200	225	225	250	275	300	325	375

Table A11. Probability of exceedence for irrigation [mm] requirements of pasture at Masterton (Te Ore Ore) on a Kokotau clay loam.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	50	75	75	100	100	100	100	125	125
Feb	50	50	50	75	75	75	75	75	100
Mar	0	25	25	25	25	50	50	50	50
Apr	0	0	0	0	0	25	25	25	25
May	0	0	0	0	0	0	0	0	0
Jun	0	0	0	0	0	0	0	0	0
Jul	0	0	0	0	0	0	0	0	0
Aug	0	0	0	0	0	0	0	0	0
Sep	0	0	0	0	0	0	0	25	25
Oct	25	25	25	25	50	50	50	50	50
Nov	25	25	50	50	50	75	75	75	75
Dec	50	75	75	75	100	100	100	100	125
Annual	325	375	375	400	400	425	450	450	500

Table A12. Probability of exceedence for irrigation [mm] requirements of pasture at Masterton (Te Ore Ore) on a Tauherenikau shallow silt loam.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	50	50	75	75	100	100	100	125	125
Feb	25	25	50	50	75	75	75	75	100
Mar	0	0	25	25	25	25	25	50	50
Apr	0	0	0	0	0	0	25	25	25
May	0	0	0	0	0	0	0	0	0
Jun	0	0	0	0	0	0	0	0	0
Jul	0	0	0	0	0	0	0	0	0
Aug	0	0	0	0	0	0	0	0	0
Sep	0	0	0	0	0	0	0	0	0
Oct	0	0	0	25	25	25	25	50	50
Nov	25	25	50	50	50	50	75	75	75
Dec	25	50	50	75	75	75	100	100	100
Annual	225	300	300	325	350	350	375	375	450

APPENDIX B - MARTINBOROUGH RESULTS

Table B1. Probability of exceedence for rainfall [mm] at Martinborough. The data are for the years 1972-2004.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	11	14	17	29	33	47	53	61	70
Feb	13	20	22	30	35	49	53	64	87
Mar	25	32	34	42	49	62	69	74	100
Apr	20	27	30	36	44	54	64	78	95
May	33	38	56	64	71	78	86	100	115
Jun	42	52	59	70	94	102	120	127	142
Jul	41	61	69	94	99	109	110	132	175
Aug	35	47	54	57	76	80	85	104	135
Sep	18	25	34	40	51	62	66	71	112
Oct	30	36	42	49	57	63	65	76	112
Nov	15	31	37	41	52	69	79	83	94
Dec	22	34	38	40	45	48	60	79	99
Annual	590	641	693	731	794	844	885	923	996

Table B2. Probability of exceedence for ET [mm] from an irrigated pasture at Martinborough on an Ahikouka silt loam.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	130	133	137	138	139	140	144	147	150
Feb	97	99	101	103	107	108	111	119	120
Mar	69	73	75	76	77	78	79	81	84
Apr	33	35	36	36	37	37	38	39	40
May	8	9	9	10	10	10	10	11	11
Jun	2	2	2	2	3	3	3	3	3
Jul	3	4	4	5	5	5	5	6	6
Aug	20	21	21	21	22	22	22	22	23
Sep	46	47	48	50	51	51	53	56	56
Oct	82	83	86	87	91	92	94	95	97
Nov	103	107	111	111	113	114	116	119	121
Dec	123	125	128	130	134	138	143	146	151
Annual	754	758	778	788	796	798	813	814	827

Table B3. Probability of exceedence for dry-matter production [kg/ha] from an irrigated pasture at Martinborough on an Ahikouka silt loam.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	2468	2518	2594	2616	2645	2662	2727	2801	2842
Feb	1839	1876	1927	1951	2029	2056	2115	2257	2272
Mar	1311	1384	1422	1444	1464	1484	1505	1538	1599
Apr	633	661	679	688	695	698	715	735	755
May	161	172	177	183	185	188	198	205	209
Jun	31	37	40	47	49	54	58	61	64
Jul	65	79	81	87	93	98	102	110	116
Aug	388	393	396	405	416	418	418	420	432
Sep	868	894	916	943	965	976	1009	1060	1070
Oct	1556	1581	1640	1652	1732	1754	1777	1803	1839
Nov	1963	2025	2100	2117	2143	2164	2210	2252	2305
Dec	2331	2371	2428	2478	2542	2622	2715	2772	2877
Annual	14318	14402	14788	14966	15115	15164	15441	15457	15715

Table B4. Probability of exceedence for ET [mm] losses from a dry-land pasture at Martinborough an Ahikouka silt loam.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	47	52	65	66	72	77	93	96	119
Feb	33	42	47	54	59	65	71	79	83
Mar	38	49	54	59	64	65	70	74	77
Apr	33	34	35	36	36	37	37	38	39
May	8	9	9	10	10	10	10	11	11
Jun	2	2	2	2	3	3	3	3	3
Jul	3	4	4	5	5	5	5	6	6
Aug	20	21	21	21	22	22	22	22	23
Sep	46	47	48	50	51	51	53	56	56
Oct	82	83	86	87	91	92	94	95	97
Nov	85	96	97	103	104	106	110	112	113
Dec	68	72	76	89	94	99	104	109	119
Annual	506	557	580	588	611	624	641	659	683

Table B5. Probability of exceedence for ET [mm] losses from a dry-land pasture at Martinborough an Kokotau clay loam.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	28	31	44	47	54	64	69	79	94
Feb	22	28	33	41	46	51	58	70	75
Mar	30	36	43	52	57	61	64	67	75
Apr	27	30	33	33	34	35	35	36	37
May	8	9	9	10	10	10	10	11	11
Jun	2	2	2	2	3	3	3	3	3
Jul	3	4	4	5	5	5	5	6	6
Aug	20	21	21	21	22	22	22	22	23
Sep	46	47	48	50	51	51	53	56	56
Oct	73	74	77	78	82	83	84	86	88
Nov	40	59	65	72	77	79	84	87	92
Dec	42	48	55	59	69	73	79	90	97
Annual	390	453	470	490	507	518	538	559	583

Table B6. Probability of exceedence for ET [mm] losses from a dry-land pasture at Martinborough a Tauherenikau shallow silt loam.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	17	21	32	35	41	52	63	73	83
Feb	13	21	24	31	35	45	52	64	73
Mar	23	30	38	48	51	58	59	66	71
Apr	18	29	31	31	32	33	35	35	37
May	8	9	9	10	10	10	10	11	11
Jun	2	2	2	2	3	3	3	3	3
Jul	3	4	4	5	5	5	5	6	6
Aug	20	21	21	21	22	22	22	22	23
Sep	46	47	48	50	51	51	53	56	56
Oct	78	82	83	83	84	86	87	92	93
Nov	31	49	57	74	76	78	82	87	91
Dec	31	34	41	43	53	59	65	84	94
Annual	343	420	428	457	474	480	512	532	556

Table B7. Probability of exceedence for rainfall [mm] at Martinborough. The data are for the years 1972-2004.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	895	985	1229	1255	1370	1464	1763	1818	2269
Feb	627	806	900	1033	1122	1238	1340	1506	1581
Mar	726	925	1019	1126	1225	1241	1333	1412	1472
Apr	622	638	664	679	689	698	711	724	740
May	161	172	177	183	185	188	198	205	209
Jun	31	37	40	47	49	54	58	61	64
Jul	65	79	81	87	93	98	102	110	116
Aug	388	393	396	405	416	418	418	420	432
Sep	868	894	916	943	965	976	1009	1060	1070
Oct	1556	1581	1640	1652	1732	1754	1777	1803	1839
Nov	1606	1833	1849	1953	1982	2005	2081	2122	2153
Dec	1285	1373	1440	1693	1788	1887	1984	2079	2265
Annual	9614	10585	11011	11168	11617	11852	12173	12515	12968

Table B8. Probability of exceedence for ET [mm] from an irrigated pasture at Martinborough on an Ahikouka silt loam.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	524	595	833	901	1028	1219	1314	1503	1790
Feb	426	534	633	782	872	961	1101	1338	1427
Mar	579	679	811	996	1089	1163	1214	1276	1419
Apr	519	574	624	633	644	661	674	689	695
May	161	165	177	183	185	188	198	205	209
Jun	31	37	40	47	49	54	58	61	64
Jul	65	79	81	87	93	98	102	110	116
Aug	388	393	396	405	416	418	418	420	432
Sep	868	894	916	943	965	976	1009	1060	1070
Oct	1384	1406	1465	1485	1552	1577	1591	1632	1675
Nov	753	1124	1242	1367	1462	1506	1595	1645	1742
Dec	801	907	1037	1120	1304	1384	1507	1705	1851
Annual	7404	8609	8928	9312	9624	9842	10230	10615	11071

Table B9. Probability of exceedence for dry-matter production [kg/ha] from an irrigated pasture at Martinborough on an Ahikouka silt loam.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	321	397	614	671	786	986	1188	1383	1577
Feb	243	403	462	598	674	856	990	1219	1388
Mar	428	578	730	919	975	1101	1130	1252	1340
Apr	345	546	581	595	613	630	657	670	695
May	151	163	172	181	185	188	197	202	209
Jun	31	37	40	47	49	54	58	61	64
Jul	65	79	81	87	93	98	102	110	116
Aug	388	393	396	405	416	418	418	420	432
Sep	868	894	916	943	965	976	1009	1060	1070
Oct	1479	1556	1569	1576	1596	1636	1644	1742	1773
Nov	591	928	1084	1398	1441	1483	1564	1662	1722
Dec	585	652	774	822	1014	1112	1237	1591	1778
Annual	6511	7984	8130	8689	9008	9128	9728	10106	10560

Table B10. Probability of exceedence for irrigation [mm] requirements of pasture at Martinborough on a Ahikouka silt loam.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	50	75	75	75	100	100	100	125	125
Feb	25	50	50	50	50	75	75	75	100
Mar	0	0	25	25	25	25	25	50	50
Apr	0	0	0	0	0	0	0	25	25
May	0	0	0	0	0	0	0	0	0
Jun	0	0	0	0	0	0	0	0	0
Jul	0	0	0	0	0	0	0	0	0
Aug	0	0	0	0	0	0	0	0	0
Sep	0	0	0	0	0	0	0	0	0
Oct	0	0	25	25	25	25	25	50	50
Nov	25	25	25	50	50	50	50	75	75
Dec	25	25	50	50	75	75	100	100	100
Annual	200	225	275	325	350	350	375	400	425

Table B11. Probability of exceedence for irrigation [mm] requirements of pasture at Martinborough on a Kokotau clay loam.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	75	75	75	100	100	100	125	125	125
Feb	50	50	75	75	75	100	100	100	100
Mar	0	25	25	25	50	50	50	50	75
Apr	0	0	0	0	25	25	25	25	25
May	0	0	0	0	0	0	0	0	0
Jun	0	0	0	0	0	0	0	0	0
Jul	0	0	0	0	0	0	0	0	0
Aug	0	0	0	0	0	0	0	0	0
Sep	0	0	0	0	0	25	25	25	25
Oct	25	25	25	50	50	50	50	50	75
Nov	50	50	50	75	75	75	75	100	100
Dec	50	75	75	75	100	100	100	125	125
Annual	375	400	450	450	475	475	500	525	550

Table B12. Probability of exceedence for irrigation [mm] requirements of pasture at Martinborough on a Tauherenikau shallow silt loam.

Month	90%	80%	70%	60%	50%	40%	30%	20%	10%
Jan	75	75	100	100	100	100	100	125	125
Feb	50	50	50	50	75	75	75	100	100
Mar	0	25	25	25	25	50	50	50	50
Apr	0	0	0	0	0	25	25	25	25
May	0	0	0	0	0	0	0	0	0
Jun	0	0	0	0	0	0	0	0	0
Jul	0	0	0	0	0	0	0	0	0
Aug	0	0	0	0	0	0	0	0	0
Sep	0	0	0	0	0	0	0	25	25
Oct	0	25	25	25	25	50	50	50	50
Nov	25	50	50	50	50	75	75	75	100
Dec	25	75	75	75	75	100	100	100	125
Annual	275	325	350	400	400	425	450	475	500

APPENDIX C: ANNUAL IRRIGATION DEMAND AND PASTURE PRODUCTION FOR THE WAIRARAPA

The uncertain and erratic nature of rainfall over the summer months means that irrigation is beneficial for pasture production in the Wiararapa region. During summer evaporative demands are at their peak and rainfall is often low. It is the uncertainty of rainfall which makes scheduling of irrigation difficult. A statistical estimate of probability is used here to define probable irrigation demand and pasture production. Since these will vary from year to year, a dependable level, rather than a mean level is used (Doorenbos and Pruit 1977; Smith 1990).

- In the case of pasture production we are interested in the lower limits that may constrain farming productivity. The *dependable level for pasture production* is defined as being the annual amount of pasture that can be grown, in say, 4 out of 5 years. This corresponds to an 80% probability of exceedence, and some 80% of the time more than this amount of pasture can be grown. However, one year in five pasture production will be less than this amount.
- In the case of irrigation demand we are interested in the upper limits that may constrain water supply. Thus, we define the *allocation level for irrigation* as being the annual amount that is required to meet the pasture requirement in 4 out of 5 years. This corresponds to a 20% probability of exceedence, and some 20% of the time more than this amount of irrigation will be required.

Time series data (daily) are used to generate the probability distributions. The lowest 20% quantile then defines the level of dependable pasture production while the upper 20% quantile defines the irrigation demand. We use the gamma distribution to describe the probability of annual irrigation and the annual pasture production on both an irrigated and a dry-land farm. The cornerstone of the gamma distribution is the gamma function which, for any real number r>0, is defined as

$$\Gamma(r) = \int_0^\infty x^{r-1} e^{-x} dx \,. \qquad \text{[Eq. C1]}$$

If X is a random variable such that

$$f_X(x) = \frac{\lambda^{\mathrm{r}}}{\Gamma(r)} x^{\mathrm{r}-1} e^{-x} dx \qquad x > 0\,, \qquad \text{[Eq. C2]}$$

then X is said to have a gamma distribution with parameters r and λ, where both r and λ must be greater than 0. The corresponding cumulative density function may be written as

$$F_X(x) = \frac{\lambda^{\mathrm{r}}}{\Gamma(r)} \int_0^R x^{r\text{-}1} e^{-x} dx \qquad \text{[Eq. C3]}$$

This function is sometimes referred to as the incomplete gamma function (Press et al. 1989). The value of $F_X(x)$ represents the probability that an event, with at least as great a magnitude as x, will occur in one time interval, while the probability of exceedence during the same time interval is given by $[1\text{-}F_X(x)]$. Thus, we can define the dependable level of pasture production as the value of x when $[1\text{-}F_X(x)] = 0.8$. Method of moment estimators for the gamma function are given by

$$\lambda = \frac{\bar{x}}{\sigma_{\mathrm{x}}{}^2} \quad , \quad r = \frac{\bar{x}^2}{\sigma_x{}^2} \qquad \text{[Eq. C4]}$$

where $\bar{x}$ and σ_x are the sample mean and standard deviation. The gamma distribution involves a number of complex integrations. Its computation is made easy because it is included as a standard function in Microsoft® Excel. The inverse gamma CDF is used to derive estimates of dependable rainfall. Calculations are presented in Tables C1 & C2.

Consider the case of pasture growing in Martinborough on an Ahikouka series soil (top panel of Table C1). The average irrigation requirement is calculated to be 330 mm per year (this corresponds to a 50% probability of exceedence, assuming 100% irrigation efficiency). This amount of irrigation should meet the pasture needs, on average, about once every two years. An irrigation allocation of 413 mm will meet pasture demands in 4 out of 5 years (a 20% probability of exceedence), while an allocation of 461 mm per year will meet the pasture needs some 9 years out of 10 (a 10% probability of exceedence). On an irrigated farm, the dependable level of pasture production is calculated to be 14.2 T DM ha^{-1} yr^{-1}. The corresponding pasture production on a dry-land farm is calculated to be just 10.7 T DM ha^{-1} yr^{-1}.

The basic aspects of the statistics of extremes can be expressed in a very simple manner. If the probability of exceedence is $E_X(x)$, then the mean return period T is simply equal to $1/E_X(x)$. This mean return period does not imply, of course, that an event of magnitude x will occur at a regular time interval of T, but that for a large number of these events the average period of time separating them will be T. With this aspect in mind, the gamma distribution curves of Tables C1 & C2 can now be used to calculate a mean return period for events of a given magnitude. In the case of irrigation, where we are interested in extreme high values, the mean return period is 5 and 10 years, respectively, for events that have a 20% and 10% probability of exceedence. In the case of pasture production, where we are interested in extreme low values, the mean return period is 5 and 10 years, respectively, for events that have a 80% and 90% probability of exceedence.

Table C1. Probability of exceedence associated with irrigation and pasture production on a range of soils in Martinborough. The blue cells represent the annual irrigation amount that will meet pasture needs in 4 out of 5 years. The green cells represent the corresponding minimum pasture production expected in 4 out of 5 years.

Site/soil	Probability of exceedance	Irrigation [mm/yr]	Irrigated pasture [T DM/ha/yr]	Dry-land pasture [T DM/ha/yr]
Martinborough Ahikouka	0.9	227	14.2	10.2
	0.8	260	14.5	10.7
	0.5	330	15.1	11.7
	0.2	413	15.6	12.7
	0.1	461	15.9	13.2
Site/soil	Probability of exceedance	Irrigation [mm/yr]	Irrigated pasture [T DM/ha/yr]	Dry-land pasture [T DM/ha/yr]
Martinborough Kokotau	0.9	372	14.2	8.0
	0.8	403	14.5	8.6
	0.5	469	15.1	9.7
	0.2	541	15.6	10.9
	0.1	581	15.9	11.5
Site/soil	Probability of exceedance	Irrigation [mm/yr]	Irrigated pasture [T DM/ha/yr]	Dry-land pasture [T DM/ha/yr]
Martinborough Tauherenikau	0.9	307	14.2	7.1
	0.8	341	14.5	7.8
	0.5	411	15.1	9.1
	0.2	490	15.6	10.4
	0.1	535	15.9	11.1

Table C2. Probability of exceedence associated with irrigation and pasture production on a range of soils in Masterton. The blue cells represent the annual irrigation amount that will meet pasture needs in 4 out of 5 years. The green cells represent the corresponding minimum pasture production expected in 4 out of 5 years.

Site/soil	Probability of exceedance	Irrigation [mm/yr]	Irrigated pasture [T DM/ha/yr]	Dry-land pasture [T DM/ha/yr]
Masterton Ahikouka	0.9	176	14.0	11.2
	0.8	203	14.3	11.6
	0.5	264	14.9	12.5
	0.2	336	15.5	13.3
	0.1	378	15.8	13.8
Site/soil	Probability of exceedance	Irrigation [mm/yr]	Irrigated pasture [T DM/ha/yr]	Dry-land pasture [T DM/ha/yr]
Masterton Kokotau	0.9	335	14.0	9.2
	0.8	362	14.3	9.7
	0.5	416	14.9	10.7
	0.2	476	15.5	11.7
	0.1	510	15.8	12.2
Site/soil	Probability of exceedance	Irrigation [mm/yr]	Irrigated pasture [T DM/ha/yr]	Dry-land pasture [T DM/ha/yr]
Masterton Tauherenikau	0.9	253	14.0	8.5
	0.8	282	14.3	9.1
	0.5	342	14.9	10.2
	0.2	410	15.5	11.4
	0.1	449	15.8	12.0